REMOTE SENSING APPLICATIONS IN FORESTRY

THE USE OF MULTISPECTRAL SENSING TECHNIQUES
TO DETECT PONDEROSA PINE TREES UNDER STRESS
FROM INSECTS OR DISEASES

by

R. C. Heller
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Pacific Southwest Forest and Range Experiment Station
Forest Service, U. S. Department of Agriculture

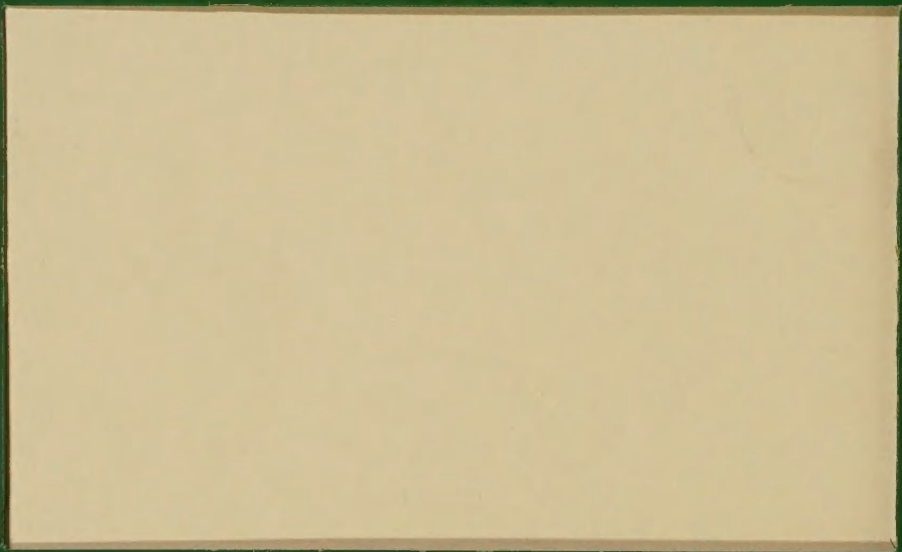Annual Progress Report   30 September, 1970

A report of research performed under the auspices of the

Forestry Remote Sensing Laboratory,
School of Forestry and Conservation
University of California
Berkeley, California

A Coordination Task Carried Out in Cooperation with
The Forest Service, U.S. Department of Agriculture

For

EARTH RESOURCES SURVEY PROGRAM
OFFICE OF SPACE SCIENCES AND APPLICATIONS
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The detection of stress induced by bark beetles in conifers is reviewed in this progress report in two sections: (1) the analysis of very small-scale aerial photographs taken by NASA's RB-57F aircraft on August 10, 1969, and (2) the analysis of multispectral imagery obtained by the optical-mechanical line scanner from the Willow Run Laboratories of the University of Michigan. Underexposure of all films taken from the RB-57 aircraft and inadequate flight coverage prevented our drawing definitive conclusions regarding optimum scales and film combinations to detect the discolored infestations. From studies made the previous year, it was apparent that large infestations, 50 meters or more in diameter, should be detectable on small-scale imagery. We could not substantiate these results from the RB-57 flight. More testing with properly exposed films will be needed before sound conclusions can be drawn on optimum scales and films.

The second section of this report relates the multispectral image preprocessing and processing of multispectral line data taken in July 1969. It relates to the ground data collected in July and August 1969 and reported in the September 1969 annual progress report. Preprocessing of the scanner signals by both analog and digital computers improved the accuracy of target recognition. Selection and ranking of the best channels for signature recognition was the greatest contribution of digital processing. Both likelihood ratio and Euclidean distance analysis were used in SPARC processing with both the visible to near IR (0.4 - 1.0 micrometers) and the three-channel IR (1.0 - 1.4 micrometers, 2.0 - 2.6 micrometers, and 4.5 to 5.5 micrometers). Target recognition was also obtained by thermal contouring of the 8.0 - 14.0 micrometers data. Improvements were made in separating hardwoods from conifers and old-kill pine trees from recent discolored trees and from healthy

trees, but accuracy of detecting the green infested trees is still not ac-
ceptable on either the SPARC or thermal-contouring processor. From our six
years of experience in processing line scan data at the University of Michi-
gan, it is clear that our greatest gain in previsual detection of stress
will occur when we can collect and process registered multispectral data
from a single aperture or common instantaneous field of view scanner system.

ACKNOWLEDGMENTS

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THE USE OF MULTISPECTRAL SENSING TECHNIQUES TO DETECT PONDEROSA PINE TREES UNDER STRESS FROM INSECTS OR DISEASES

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INTRODUCTION

As a result of our joint NASA studies over the past four years, we have learned a great deal about how to measure physiological stress in forest vegetation. For example, we now know the rate of foliage color change over time for healthy and stressed ponderosa pine (Pinus ponderosa, Laws.) and how this discoloration shows up on spectrographs and Munsell notations. In measuring the energy budget of instrumented healthy and dying trees, we learned that radiance differences occur but only under certain physical and meteorological conditions. The sun must be shining, the xylem tissues partially occluded (in stress trees), and soil moisture below field capacity. Under these conditions a 2° to 5° C. (Celsius) temperature does occur--the stressed trees being warmer.

Our photographs taken at large scale (1:1,584) show that color films discriminate healthy from stressed trees, but only when discoloration begins. In other words, neither color nor false-color film (Kodak Aerochrome Infrared, Type 2443) can be used as a previsual sensor of stress.

As a result of our NASA studies we recommend that color or false-color photos be taken at periods of maximum foliage contrast in making operational surveys for detection of bark beetle-killed conifers. In the Black Hills, this time period extends from mid-August to early October of the year following beetle attack. A two stage probability sampling survey made at this time is

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the most efficient design. Our studies show that small-scale photos (1:32,000) of an entire infested area will serve as a sampling frame for selecting sample strip photography (1.6 by 16 kilometers) at a larger scale (1:8,000). Infestations larger than four trees (or 6 meters in diameter) can be detected fairly well on the small-scale photos, but best accuracy is attained on the larger scale (1:8,000) where single trees (3 meters in diameter) can be detected best.

In 1969, we described the ability of photo interpreters to identify various sizes of infestations (3 to 150 meters in diameter) on increasingly smaller scales of color photography. This work is directed at (1) determining the optimum altitudes and films for making bark beetle surveys over large areas and (2) learning what size infestation (target size) we can expect to pick up on ERTS imagery. The RB-57 flight on August 8, 1969, provided us with the smallest scale photography ever taken over the Black Hills. The results of photo interpretation and assessment of image quality are described in the first part of this report.

The second section of the report describes multispectral processing of imagery taken in July 1969 by the University of Michigan's multispectral system. Many improvements in image preprocessing make target recognition of vegetation types more reliable. The hybrid processing techniques used and accuracies obtained are discussed in detail.

Both the aerial photography and multispectral scanning tests were conducted over the 1.6- by 4.8-kilometer study site in the Black Hills of South Dakota. The locations, sizes in meters (or feet), and counts of trees per infestation were surveyed and mapped in August 1969 (Figure 1).
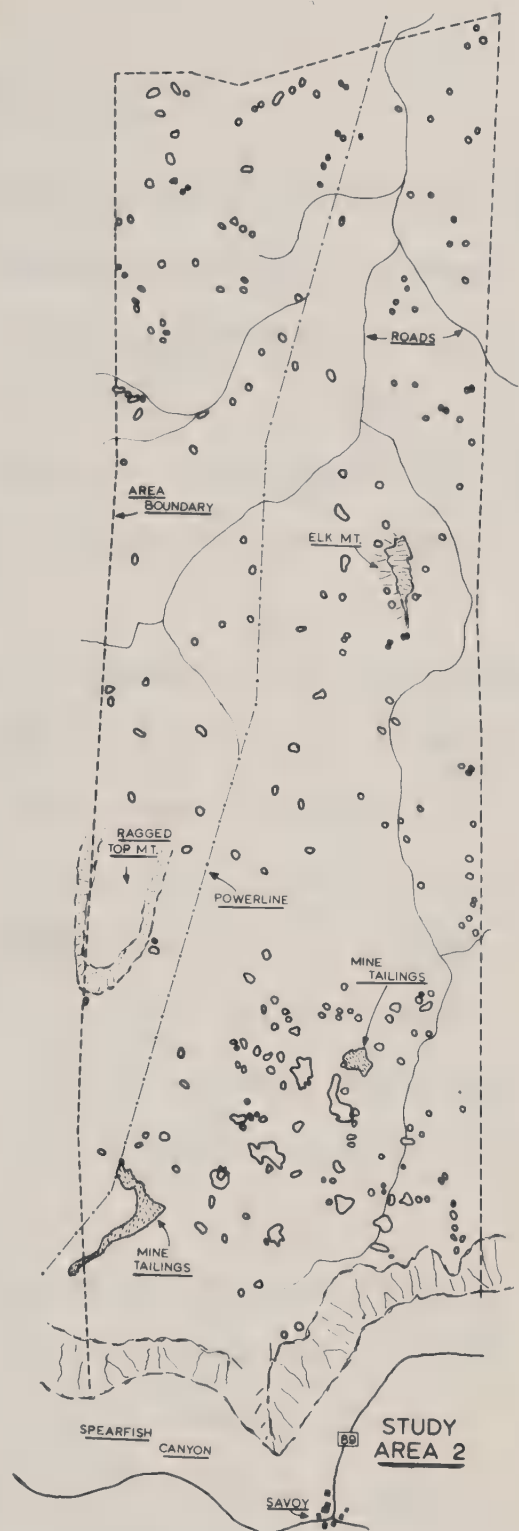
Figure 1. Aerial mosaic on left of 1.6 by 5 kilometer study area near Lead,
South Dakota. On right, 211 infestations of various sizes (3 to
200 meters) are plotted at the same scale. Note the gold tailings
pile which appears on all large and small-scale imagery; it
measures about 80 meters and affords the reader a recognizable
target of known size.

HIGH-FLIGHT EXPERIMENT (RB-57)

On August 8, 1969, the NASA RB-57 aircraft on Mission #101 exposed various films at three small scales of photography along three designated flight lines covering the northern part of the Black Hills National Forest. Photographic coverage resulting from the RB-57 flight was to include previously photographed (1968, 1969) Study Area II and ten 1.6- x 16-kilometer (1- x 10-mile) sample strips (Figure 2). Film/filter-scale combinations exposed by the RB-57 are listed in Table 1.

During the same month as the RB-57 flight, members of the Forest Service Remote Sensing Project in Berkeley used a Zeiss RMK 21/23 aerial camera to take large-scale (1:8,000) Anscochrome D/200 photographs over the same 1.6- x 16-kilometer sample strips. This large-scale photography was part of a multistage probability sampling system to estimate the impact of a bark beetle epidemic on the Black Hills National Forest in 1969. The purpose of the RB-57 flight was to compare the smaller scales of the RB-57 photography with the 1:8,000 scale and develop a statistical relationship between them which could be used in the sampling system.

There were three main objectives in exposing and interpreting the RB-57 imagery: (1) to study a much larger area with more varied conditions than Study Area II, (2) to evaluate several film/filter combinations not used previously in the Black Hills--color SO 117/12 filter, panchromatic 3400/58 filter, panchromatic 3400/25A filter, and Aerographic infrared SO 246/89B filter, and (3) to find out what resolution size (or infestation size class) could be detected on 1:220,000 scale imagery.

As discussed in detail in the 90-day report (1) some crucial errors were made during photography. The actual RB-57 flight line locations did not
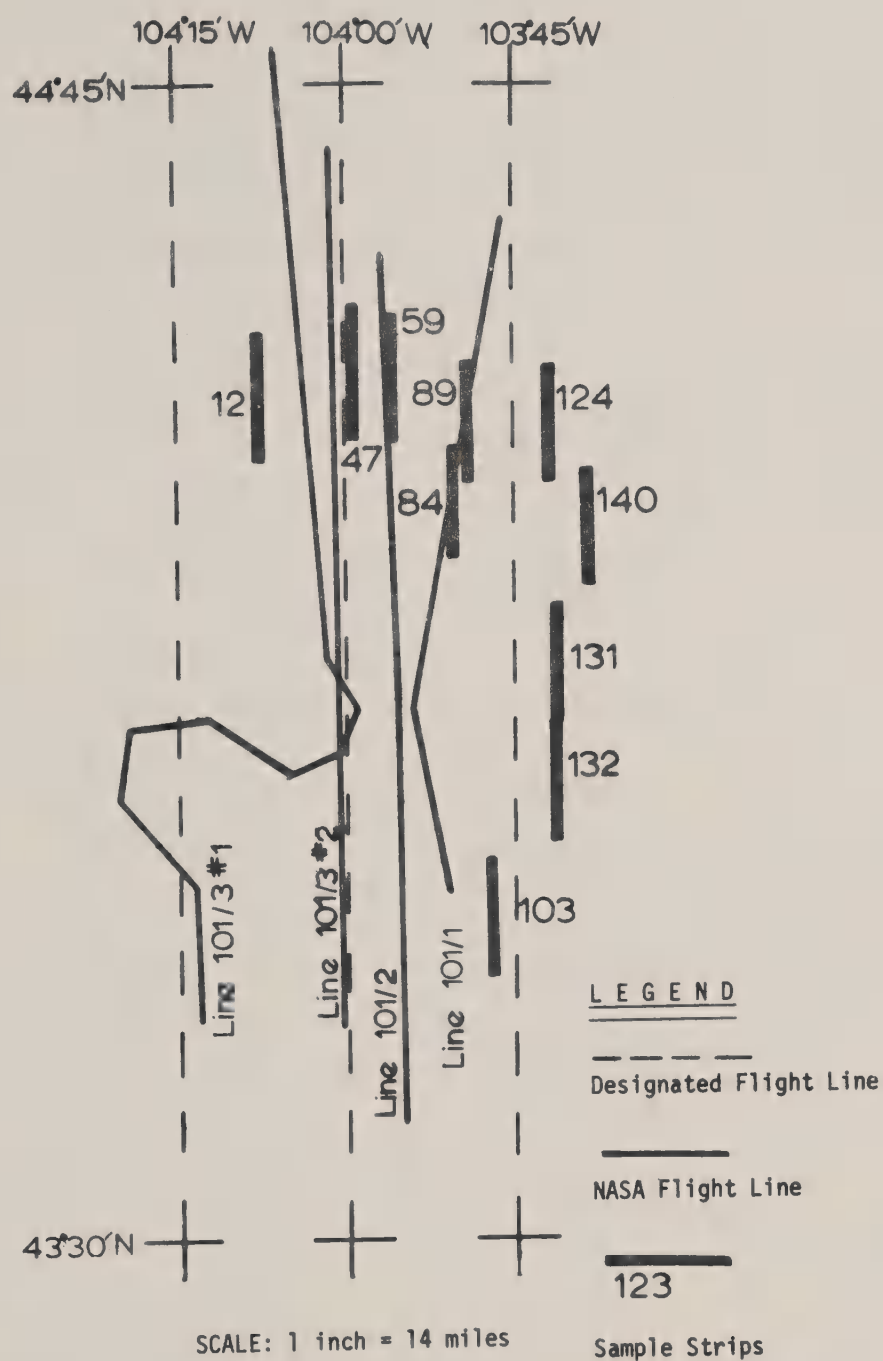
Figure 2. Flight coverage of NASA RB-57, August 1969. Dashed lines show desired flight line locations. Solid lines show actual NASA flight lines. Heavy lines show location of 10 sample strips-- each 1.6 x 16 kilometers, taken on color film at 1:8,000 scale.

Table 1. Film-filter-scale combinations exposed during RB-57 flight mission #101

FILM	FILTER	CAMERA	FOCAL LENGTH	SCALE	FORMAT
Color IR (SO 117)	Zeiss "B" (15)	Zeiss	12"	1:55,000	9"
Color (2448)	HF 3	RC-8	6"	1:110,000	9"
Color IR (SO 117)	15	RC-8	6"	1:110,000	9"
Color (SO 368)	2A	Hasselblad	3"	1:220,000	70 mm
Color (SO 368)	12	Hasselblad	3"	1:220,000	70 mm
Color IR (SO 180)	15g	Hasselblad	3"	1:220,000	70 mm
Panchromatic (3400)	58	Hasselblad	3"	1:220,000	70 mm
Panchromatic (3400)	25A	Hasselblad	3"	1:220,000	70 mm
Panchromatic IR (SO 246)	89B	Hasselblad	3"	1:220,000	70 mm

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coincide with the locations on the flight plan (see Figure 2), so the desired coverage was not obtained. Only four out of the ten 1.6- by 16-kilometer sample strips (lines 47, 59, 84 and 89) were obtained on all scales.

Almost all the high-flight films were underexposed from one to one-and-one-half field stops. It appears that exposure settings were calibrated over agricultural lands north and south of the forest area rather than over the forest. As a result, most of the duplicate transparencies sent to us were very dark, causing poorer resolution and dark shadows along the north facing slopes which obscured even high contrast targets (Figures 3, 4 and 5). Transparencies from two of the panchromatic films (3400 used with Wratten 25A and 58 filters) were so dark that they were returned to NASA for reprocessing at one-half the original density. Only two of the nine film types were properly exposed--the color film with a minus blue filter and the Ektachrome infrared with a Wratten 15 filter, both at 1:220,000 scale (Figure 5).

INTERPRETATION PROCEDURES

To prepare the transparencies for photo interpretation, clear acetate templates were placed over the film and the areas to be interpreted were delineated.

All films were examined by one interpreter who had no prior experience with the Black Hills beetle study. She had received some training before beginning interpretation.

Study Area II was interpreted first on all films. Preliminary results and conclusions based on the study area were discussed in the 90-day report.[1] Then, the four sample strips of the RB-57 photography (lines 47, 59, 84 and 89) were interpreted on all films and scales.

Transparencies were viewed stereoscopically, each suspected beetle infestation plotted, and the number of trees in each group counted (or estimated) and
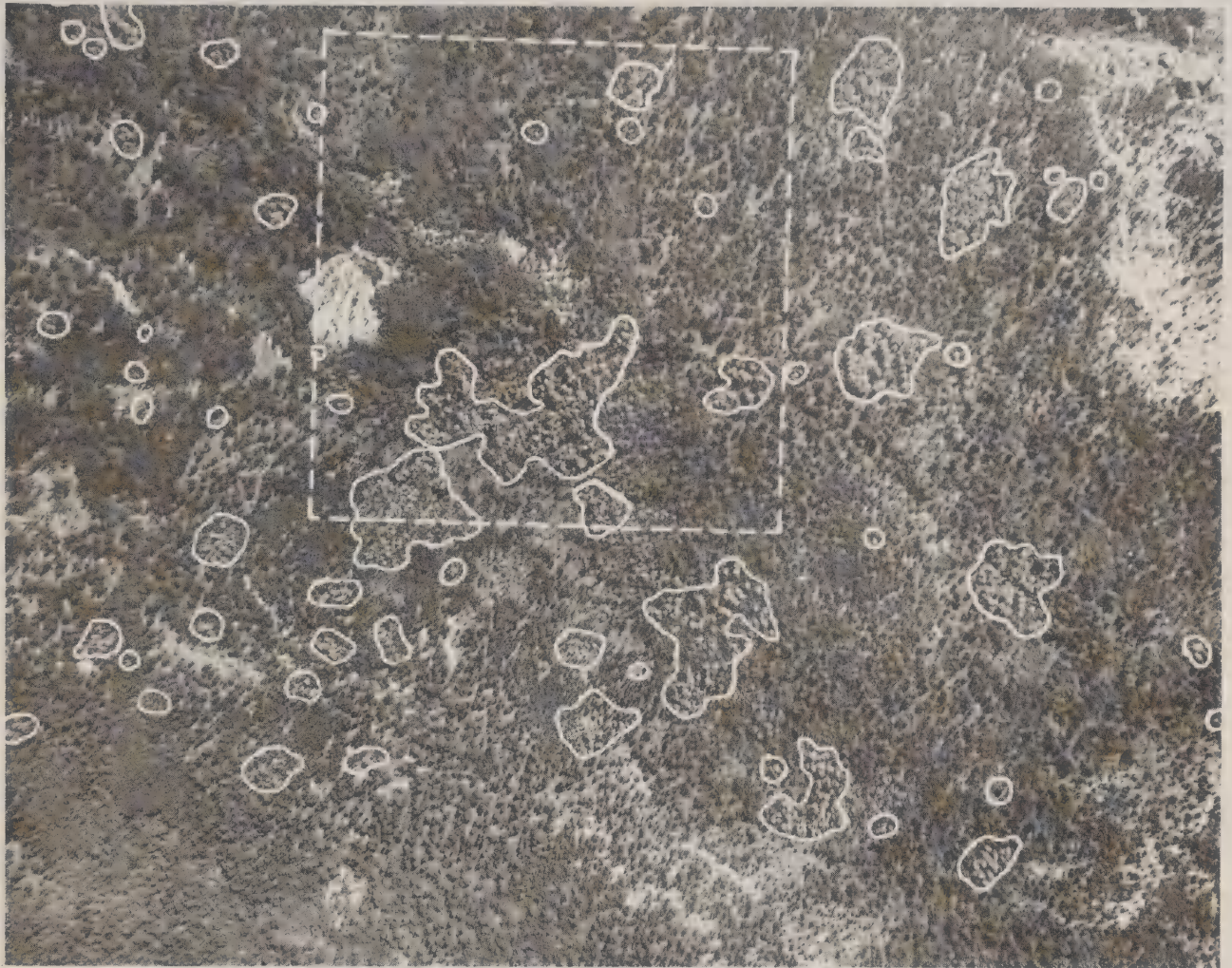
Figure 3. Color photograph taken on August 11, 1969, with a Zeiss 21/23 aerial
camera over Study Area II--scale 1:8,000. Bark beetle infestations
are outlined in white. The focus of interest for processing the
Michigan multispectral data is within the broken line. Compare ex-
posure and resolution to RB-57 photographs of the same area on
Figures 4 and 5.

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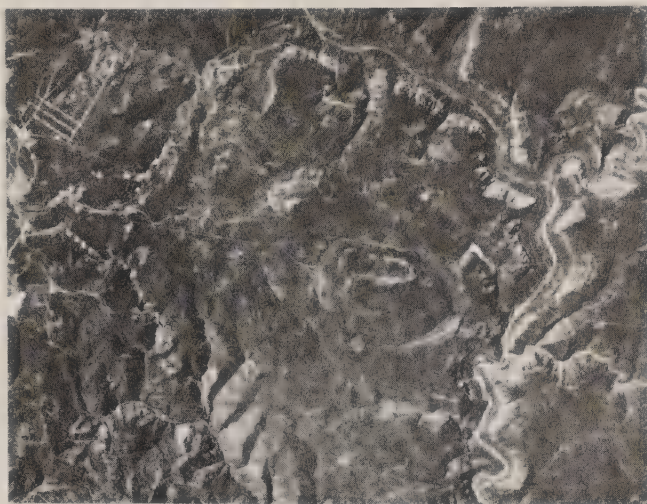
(a) 1:110,000

(b) 1:110,000
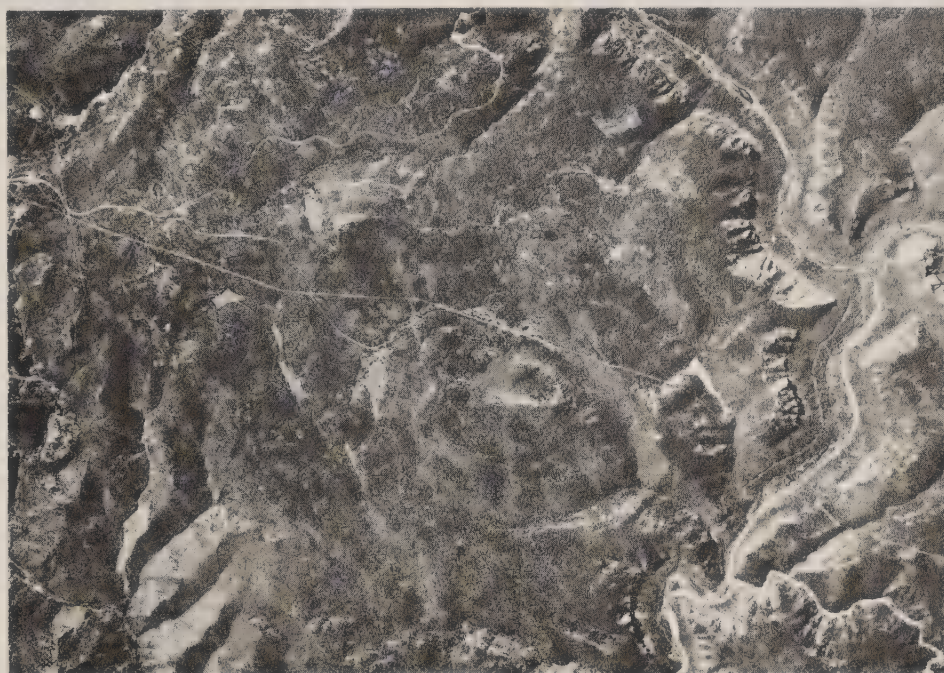
(c) 1:55,000

Figure 4. RB-57 coverage of Study Area II. (a) RC-8 152 mm Ektachrome (2440) + HF 3; (b) RC-8 152 mm Ektachrome infrared (SO 117) + 15; (c) Zeiss 304 mm Ektachrome infrared (SO 117) + "B" (15). Most forested areas were underexposed.

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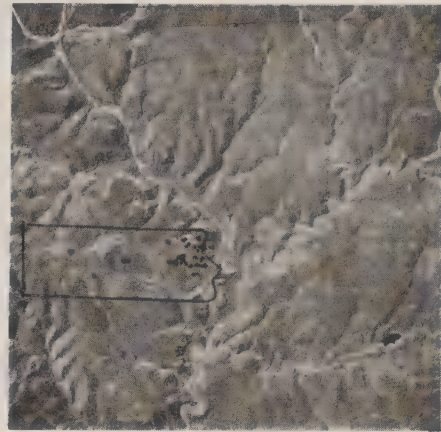
(a) 1:220,000   (b) 1:220,000
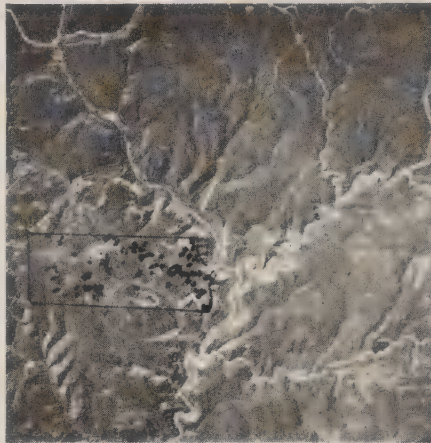
(c) 1:220,000

Figure 5. Hasselblad imagery of Study Area II. (a) color (SO 368) + 2A; (b) color infrared (SO 180) + 15; (c) color (SO 368) + 12.

recorded. In previous studies of the Black Hills beetle (1968, 1969), both location of an interpreted infestation spot and its tree count had been numbered. When photo templates were compared with the ground truth information, both the location and size class estimate (Table 2) of an infestation had to match the ground truth information in order for the interpretation to be a <u>correct</u> <u>call</u>.

Because the scales of the RB-57 photography were so small, no attempt was made to number the location and tree count of a particular infestation. This created problems in evaluating the results and will be discussed in a later section.

To evaluate photo interpretation, the 1:8,000 scale Zeiss imagery was used as ground truth. Only the location of each infestation plotted by the interpreter on the RB-57 imagery was compared to the 1:8,000 scale. An interpretation was called correct if in the proper location, a commission error if in a wrong location, or an omission error if the infestation was not plotted.

INTERPRETATION RESULTS

Photo interpretation results are shown in terms of percent detection of the four different size class categories discussed earlier. Figure 6 shows detection success by film type and scale on Study Area II alone, while Figure 7 shows success on the four 1.6- x 16-kilometer strips. These two graphs may be compared to Figure 8, which shows results from the film/scale combinations photographed, interpreted, and analyzed in 1969. Figure 8, like Figure 6, represents interpretation of only Study Area II.

On all three graphs, the level of detection tends to decrease as scale gets smaller and as infestation size decreases. Figure 8 shows comparable decreases in detection with size class and scale decrease for both Ektachrome IR and Anscochrome D/200 films. The great difference in detection success between

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Table 2. Relationship of number of trees to target size.[1]

Number of trees	Size in meters (average largest dimension)
1 - 3	0 - 6
4 - 10	7 - 15
11 - 20	16 - 30
21 +	31 +

[1]Ground measurements showed that the number of discolored trees in an infested group was related to a particular target or infestation size on the ground. (Ability to detect a particular target size on a photograph relates to the resolution capabilities of that photograph.) For convenience, four group and target sizes were chosen.
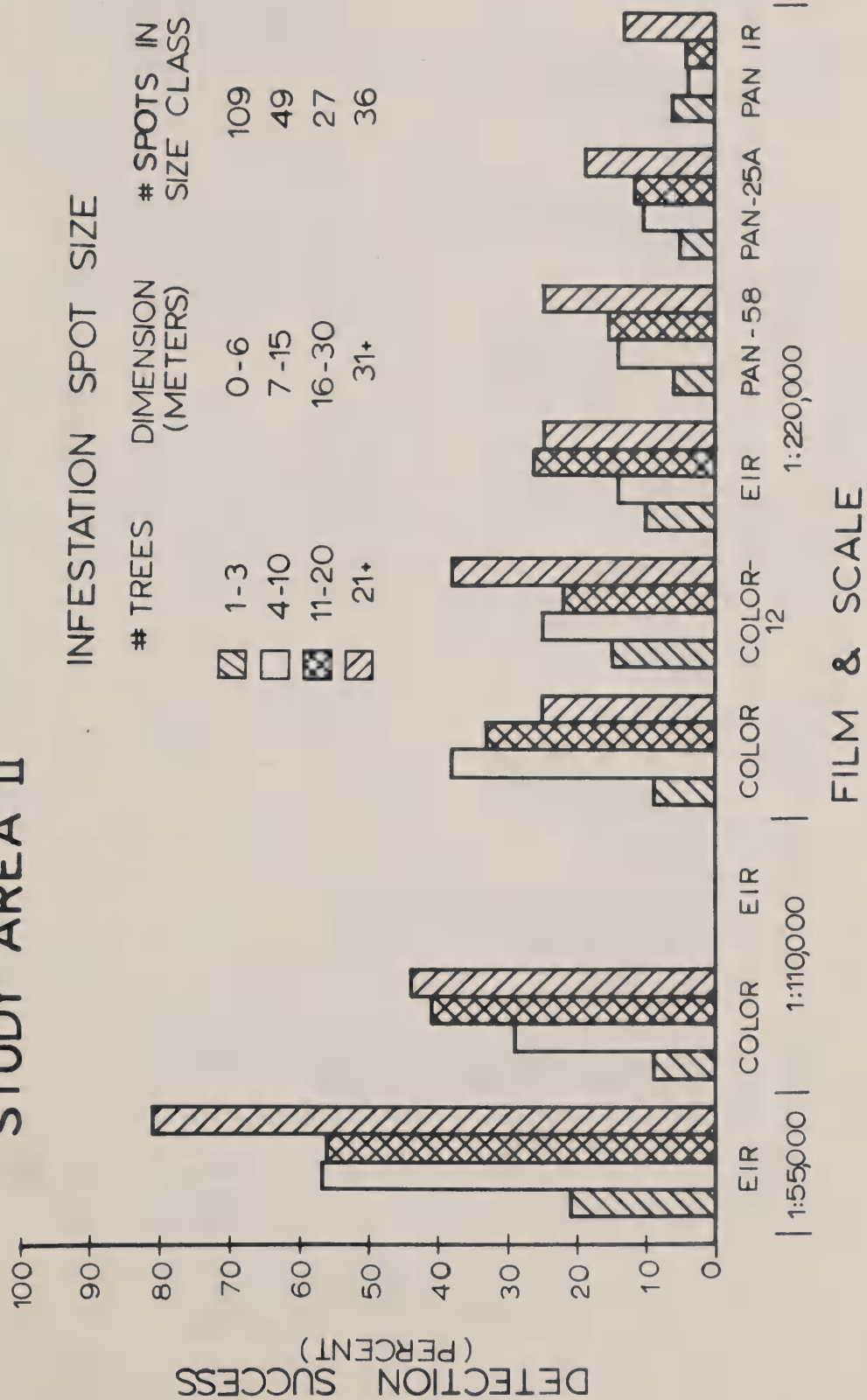
Figure 6. Detection success by scale and size of infestation on RB-57 imagery of Study Area II.

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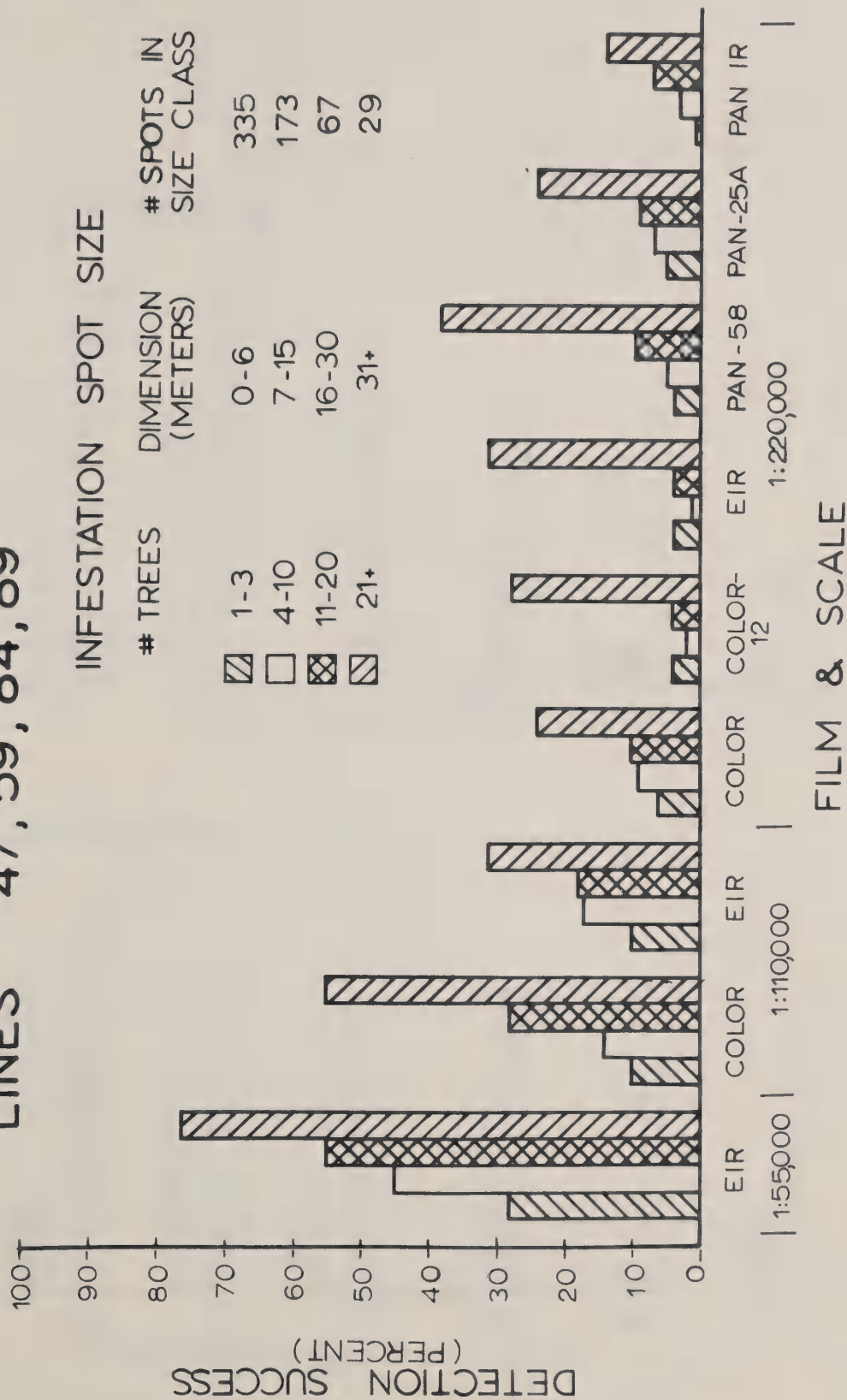
Figure 7. Detection success of various scales and films over four 1.6- x 16-kilometer sample strips photo-graphed by RB-57.

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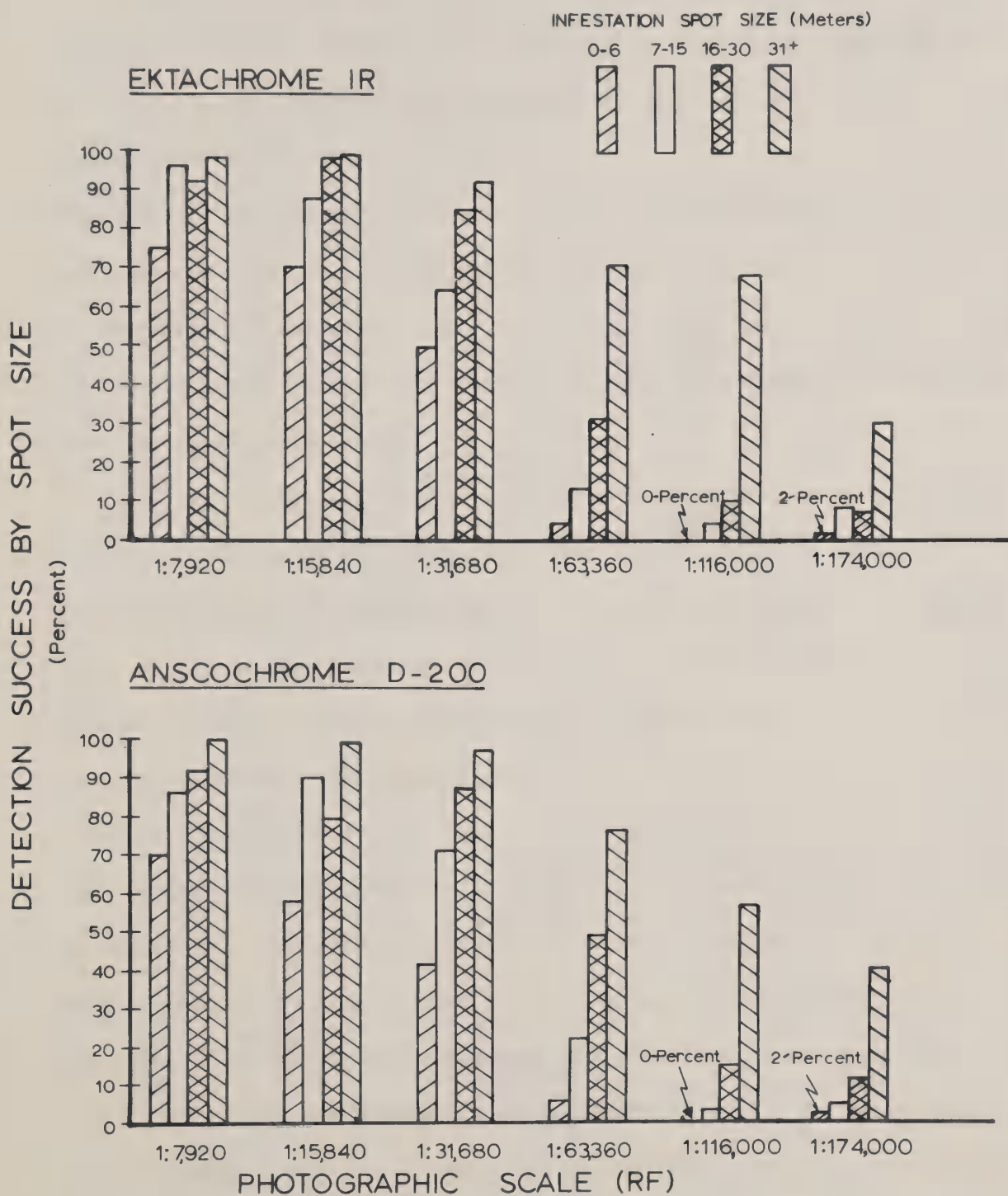
Figure 8. Detection success on well-exposed color and color infrared film over Study Area II, taken by Forest Service Remote Sensing Project in August 1969.

the largest size class (21+ trees) and the three other classes led to conclusions in the 1969 NASA annual report[2] that only this largest size class could be detected with any degree of success on smaller scales (1:63,360 or less).

The bar graphs on Figure 6 do not show quite as clear a pattern of decrease in accuracy as the ones on Figure 7. There is a general decline in detection success on the RB-57 photograph as size class and scale become smaller. But on none of the films or scales is there such a marked division between detection of the largest size class and of the three smaller classes as was seen on Figure 8. Success in detection of these three classes is noticeably higher on the RB-57 photography. (No values are given for the Ektachrome IR film at 1:110,000 scale because the portion of this film covering Study Area II was too dark to be interpreted.)

Three things which contributed to a difference in photo interpretation results from the RB-57 photography may help to explain Figure 6. First, the poor quality of the imagery may have caused lower detection overall; it may also have masked any differences in the resolution capabilities of the films being tested. Second, correct location was the only criterion in deciding whether or not an interpreted spot was a correct call. In Study Area II a large number of infestation groups of all sizes are concentrated on a very small area, particularly when viewed at 1:220,000 scale (Figure 5). In many cases, several small groups of trees in close proximity could be seen by the interpreter as one larger group and marked on the template as such. These small groups were later scored correct calls as if they had been detected individually, since they had been marked in the right location. Third, on such extremely small scales as 1:220,000, the interpreter's ink dot over an infestation often covered a much greater area than intended and may also have covered infestations which were not seen. It seems, therefore, that the methods of interpretation were more responsible than any

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other factor for improved success in detection of the smaller size classes indicated on Figure 6. Perhaps in the future, enlargement of the transparencies to be interpreted could remedy this situation.

On Figure 7, the results for sample lines 47, 58, 84, and 89 are shown. Detection scores for the largest infestation size class are similar to those on both Figures 6 and 8. For the smaller size classes, detection is lower than it was on Study Area II probably because infestations are not as concentrated on the 1.6- x 16-kilometer strips as they are on the study area.

As has been shown in previous studies, the greatest number of infestation groups undetected by photo interpreters was of the smallest size class (1-3 trees). The small targets accounted for well over 60 percent of the omission errors on any scale or film. As scale decreases, the overall number of omission errors increases, particularly in this smallest category.

Commission errors were also very large, and again concentrated in the 1-3 tree size class. However, the number of commission errors decreases as photo scale gets smaller. If you cannot see them, you do not misplot them.

MULTISPECTRAL COMBINING

As a final effort to glean information from the RB-57 imagery, the three black-and-white Hasselblad transparencies at 1:220,000 scale were combined in multispectral projector at the School of Forestry and Conservation, University of California at Berkeley. It was hoped that these transparencies would yield more information when combined with filters than either the color films or the black-and-white transparencies had individually. The panchromatic 3400 trans- parency with a Wratten 58 filter was projected through a Wratten 47A filter, the Pan 3400 transparency with a Wratten 25A filter through a Wratten 102 filter and the Pan IR SO 246/89B filter through a Wratten 25 filter. The filters in

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the projector were chosen to enhance the color of infestation groups. The three panchromatic images were superimposed and adjusted until they appeared as one color infrared image on the screen (Figure 9).

Unfortunately, no new information appeared due to difficulties in projecting light through such dark transparencies. However, this method may prove fruitful in future studies of Black Hills beetle infestations if better quality imagery is used.

DISCUSSION

In the 90-day report,[1] several preliminary conclusions regarding film capabilities were offered (i.e., that color film with a minus blue filter at 1:220,000 seemed to be the best combination at that scale). It now appears that extraneous factors such as variations in exposure, the methods of photo interpretation and a lack of complete photo coverage are more relevant to the actual "data" obtained than are the relative capabilities of the films tested. Looking back to the three objectives of this study (best film/filter combination, test over a large area, and determination of resolution size) one sees that none of them has really been accomplished. Therefore, no definite conclusions can be derived. More care in obtaining the imagery should be taken in subsequent studies so that valuable research funds and time are put to more constructive use.

MULTISPECTRAL IMAGE COLLECTION AND PROCESSING

PROCEDURES

Airborne

All airborne data collection reported here was performed by the University of Michigan multispectral system during the summer of 1969. It is being reported

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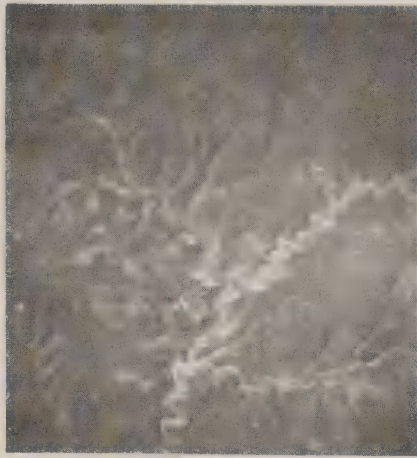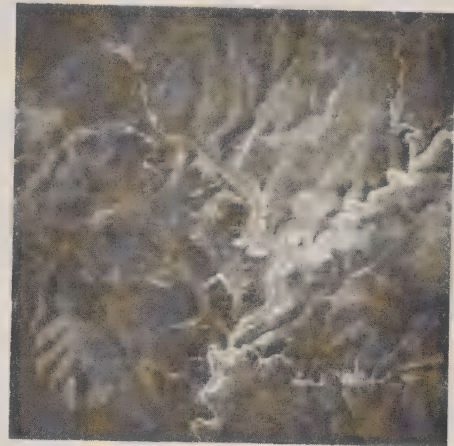
Figure 9. Panchromatic Hasselblad imagery over Study Area II was combined in multispectral projector to produce a simulated color infrared image. A. Panchromatic (3400) + Wratten 58 filter. B. Panchromatic 3400 + Wratten 25A filter. C. Aerographic Infrared (SO 246) + Wratten 89B filter. D. Multispectral combination.

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at this time because analysis of the fully processed data was just completed. Airborne flights over the Black Hills test site occurred on July 21 and 22, 1969. A single flight line was flown at three altitudes from east to west: (1) 1,500 feet, (2) 5,000 feet, and (3) 7,500 feet above a mean ground datum of 6,000 feet above sea level.

Flights were made beginning at 1000 and 1430 sun time on July 21, and 0730 and 1230 on July 22. Runs at each altitude were duplicated during each flight so as to insure adequate data for each diurnal period. This resulted in a total of 34 runs during the two-day period.

Aerial cameras. Four J. A Maurer, P-220, 70 mm aerial cameras and two Maurer KB-8 70 mm aerial cameras recorded photographic data from the Michigan C-47 aircraft. Each of the P-220 cameras was fitted with a 75 mm lens and the KB-8's had 150 mm lenses. All cameras were operated at the maximum shutter speed permitted by the combination of optical aperture and film emulsion speed. The P-220 cameras were loaded with the following films: (1) Aerial Plus-X panchromatic film with a Wratten 25A (red) filter, (2) Aerographic infrared film (black-and-white) with a Wratten 25A (red) filter, (3) Ektachrome film with a Wratten 1A (haze cutting) filter, and (4) Ektachrome infrared film with a Wratten 12 filter. The purpose of the 150 mm lenses was to provide coverage comparable to the 37° field of view of the first multispectral scanner, while the 75 mm lenses provided coverage comparable to the 80° field of view of the second multispectral scanner.

Optical-mechanical scanners. The University of Michigan's multispectral scanning system flown on this study consisted of two separate double-ended optical-mechanical scanners. The primary element of the scanning system was a spectrometer which provided automatic registration in both time and position for 10 of 12 possible discrete spectral bands in the visible and near-infrared from

0.4 to 1.0 micrometers (μm). End B of the same scanner which contained the spectrometer was fitted with a three-element detector sensitive in the bands 1.0 - 1.4 μm, 1.5 - 1.8 μm, and 2.0 - 2.6 μm. During each rotation of the scanning mirror, the field of view was in the following sequence: (1) 80 angular degrees of ground data, (2) two radiance-calibrated tungsten filament lamps, and (3) the dark interior of the scanner housing. End A of the second scanner was fitted with a narrow field of view (37°) and a three-element detector sensitive in the bands 1.0 - 1.4 μm, 2.0 - 2.6 μm, and 4.5 - 5.5 μm. End B had a cooled Hg:Ge detector sensitive in the range 8.2 - 13.5 μm. The second scanner housing was equipped with two temperature controlled blackbody plates which were viewed sequentially with the ground scene giving an apparent temperature calibration to the thermal imagery.

Scanner data were recorded in analog form on one 14-track tape recorder and one 7-track tape recorder. All data channels provided quantitative data in both relative and absolute measure through preservation of DC (electrical) signal levels and the registration of known levels of radiance for referencing during each scan. Simultaneous calibration and referencing provided rapid access to the data back in the laboratory. Radio communication between the airborne system operators and the ground crew provided minute by minute ground data for setting airborne system reference levels.

Multispectral Processing

All processing of multispectral data was completed at the University of Michigan's Willow Run Laboratories under a master contract NAS 9-9784 for data processing monitored by NASA, Manned Spacecraft Center, TF-8.

By November 1969, all aircraft tapes had been duplicated and the preliminary viewing of all video data was completed. At that time, the best runs were

selected for intensive processing and analysis, and plans for data processing were worked out with Michigan and our NASA Technical Monitor.

Because the data from several channels were recorded in registration and were referenced, a number of analog and digital processing techniques were available. Multispectral data processing techniques were restricted to three synchronous data sets: (1) 0.4 - 1.0 μm, 10-channel spectrometer data, (2) 1.0 - 2.6 μm three element array data, and (3) 1.0 - 5.5 μm three element array data. Single-band processing techniques, both analog and digital, were applicable to any single channel of video data but most emphasis was given to processing thermal infrared (8 - 14 μm) data.

Digital Processing. The statistical decision criteria for recognition processing (both thermal and nonthermal) were performed with digital techniques. Also, digital pre-processing programs were used to remove unwanted variations in the data due to angle effects, shadows, and possible scanner nonuniform response over the total field of view so as to increase accuracy of recognition over the entire imaged flight line.

Channel optimization processing -- In the past, the selection and weighting of spectrometer channels for visible and near infrared data were often done in somewhat less than a scientific procedure. A more scientific approach was developed at the Willow Run Laboratories wherein a digital computer was used to select the optimum spectrometer channels for a classification problem.

The optimum channel selection technique was tested on three classification problems. The first was a generalized forest type classification to identify hardwoods (Betula sp. and Populus sp.), healthy ponderosa pine (Pinus ponderosa Laws.), dead ponderosa pine killed by the mountain pine beetle (Dendroctonus

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<u>ponderosae</u> Hopk.), and grass-covered openings. The accepted common name for this bark beetle has now been changed from the Black Hills beetle to the mountain pine beetle.

The second problem was to classify three conditions of vigor in ponderosa pine: (1) healthy, (2) beetle attacked having green foliage, and (3) dead with a small amount of red foliage retained. The third problem was to classify healthy ponderosa pine and beetle attacked pine with green foliage. Data for the spectrometer channel optimization study were collected over the Black Hills test site at 1347 hours on July 22, 1969, at an altitude of 1,500 feet above the ground. All data processing was done on the CDC 1604B computer maintained at the Willow Run Laboratories.

Data from the aircraft analog tapes were first converted to digital form by using Michigan's special purpose interface gear associated with the digital computer and the software program ATOD. Because of the inherent small size of features of interest in forests, a very careful job was done on deskewing the original tape to preserve spatial relationship. In a further attempt to maintain spatial resolution, every scan line and each resolution element of the analog data were digitized. After data conversion two special purpose test programs were run on the data. ADTEST and AUTOCAL, for measuring residual skew and for determining dark levels.

Program GRAYMAP was run on the data next to obtain a pictorial display of the data and to determine the location of the training sets.[*] Two graymaps of the data were made, the first of the 0.8 - 1.0 μm channel and the second of the 0.46 - 0.48 μm channel. The former map was used to stratify hardwoods from pine and the latter map to stratify pine and other vegetation from bare soil and rock.

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[*]A training set is a contiguous area of uniform type which can be electronically or mathematically relocated on command. It is used as a relocatable area for defining the spectral nature of a particular forest type or feature.

Training sets were located on the graymaps by carefully transferring their location from high-resolution 1:8,000 scale aerial color photography. The color photography was obtained five weeks later in the season than the multi-spectral imagery, at a time when all the beetle killed trees were clearly dis-colored and could be positively identified. The training sets used were hard-woods, grassy openings, two categories of healthy pine (different stand densi-ties), two categories of beetle attacked pine (one green trees and the other yellow-green trees), and beetle killed pine from previous years.

After the training sets were located on the graymaps, their digital loca-tion was used as input to the program IMPROVE, which calculated the spectral signatures of the training sets. The signatures of the training sets were care-fully checked to insure that they actually represented the target areas.

The outputs of the program IMPROVE were a listing of the signatures (means, standard deviations, and correlation matrix) and a set of punched cards with the same information. The punched cards were used as input to the program STEPER 2 which computed optimum channels. The program operated by assuming the signatures represent Gaussian random variables, an assumption which is good for the data examined thus far. STEPER 2 computed the average probability of mis-classification for each pair of signatures which, for example, is the probability of misclassifying signature 2 as signature 1. Then the program adds the average probabilities of misclassification, weighting each entry. The result is an average pairwise probability of misclassification. The best channel was chosen as that channel which has the lowest average pairwise probability of misclassi-fication (APPM). The second best channel is chosen as that channel which, along with the best single channel, has the lowest average probability of misclassifi-cation for all signature pairs. The third best channel is similarly chosen, etc., until all channels have been ordered.

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Thermal processing -- A technique was developed for looking at the response of the thermal (8 - 14 μm) detector in digital form. A computer program was written to convert the analog signals, with calibration data, to digital format. The thermal data were sampled 3.8 times per resolution element and quantized before being recorded on digital tapes at 200 BPI. Subsequently, the data were converted to 556 BPI and short records to be compatible with the 1108 computer facility in Berkeley.

The Michigan computer facility produced graymap outputs of the digitized thermal data. Every fourth digitized point and every scan line were printed by the graymap routine. Seven character/densities were used to represent radiance variations within the flight line scene. A digitized range was assigned each characterization and the sensitivity of the display technique could be manipulated depending on the size of each range. That is, the density levels were spread over both a wide and a very narrow apparent scene temperature range. Scan samples and scan lines were numbered on the computer graymap and were easily related to a 3X enlargement of the thermal analog filmstrip for point identification.

Analog Processing.

SPARC processing.-- Processing experiments were conducted at Willow Run Laboratories with a special Spectral Processing and Recognition Computer (SPARC). Three-channel processing (1.0 - 1.4 μm, 2.0 - 2.6 μm, and 4.5 - 5.5 μm) was implemented as a separate SPARC process in addition to the normal 10-channel spectrometer processing. This was planned because past experience showed that many classification errors were made in identifying tree vigor when only visible and near infrared data were used (0.4 - 1.0 μm).

Two separate operations were performed on the SPARC. The first consisted of selecting a training sample from the data (that is, some known point or area

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in the test scene) and storing the spectral characteristics of that area in the computer. Training sets were selected to describe the total forest scene at the Black Hills test site as nearly as possible. They were: (1) hardwoods, (2) grassy clearings, (3) healthy ponderosa pine, (4) green beetle attacked ponderosa pine, and (5) dead beetle killed ponderosa pine. The next operation consisted of recognizing all points in the scene which were statistically similar to the spectrum from the training set. A strip map was prepared wherein all points with similar spectral properties were printed as enhanced images.

Implementation of the likelihood ratio processing on SPARC was according to standard practice. By using tape loop training sets and entering spectral signature information consisting of means and standard deviations of signals in each spectral channel and covariances between channels, it was possible to generate the assumed Gaussian probability density function for each training set.

The value of this function is a measure of how closely a set of voltages from an area outside the training set match the training set voltages. The voltages of each channel are proportional to the spectral radiance in that channel. Thus, the assumption in processing--to identify tree vigor--is that the spectral radiance of each tree in a class is characteristic of the overall class. The biophysical and physiological implications of this rationale have been discussed in detail (Weber, 1969).

After the probability density functions (PDF) were determined, processing was done by Euclidean distance analysis wherein only scene points which matched the training set signature for the condition class to be recognized were printed out. This was achieved by printing out only the scene points where PDF's were greater than a certain threshold which was set with a priori knowledge. The

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threshold was changed each time to vary the criterion of how well an unknown
tree matched a training set of known vigor condition.

The second way unknown data were processed over the Black Hills test site
was by the more sophisticated likelihood ratio process. Instead of asking whether
the value of the PDF for a desired tree condition class was larger than a
certain acceptance threshold for a set of voltages from an unknown scene, the
SPARC determines whether the value of the likelihood ratio is greater than the
threshold. There were, of course, many likelihood ratios--basically ratios of
PDF's. The likelihood ratio implemented by SPARC was:

$$L = \frac{PDF\ (target)}{\Sigma PDF\ (backgrounds)}$$, where L = likelihood ratio,
  PDF = probability density function
  ΣPDF = probability density function
       of background (sum of all
       probability density functions).

There were special problems in working with three-element infrared data.
Because of the small size of the targets (individual trees) and the design of
the three element detector, raw data were not precisely registered. To achieve
this necessary registration, specially designed delay lines were designed into
the circuitry for this investigation to bring signals into exact registration.

Thermal contouring -- Specialized single-channel processing was used
with the thermal 8 - 14 µm channel data to produce a set of voltage slices
corresponding to different temperature intervals. Since the raw data were
originally stored on magnetic tape, the electronic slicing was performed easily
and more accurately than if the object were photographed and subsequently
scanned with a densitometer over the grey tones of the film.

The technique consisted of slicing the thermal data into a number of
equal size voltage increments (usually ten), printing the data contained in
each of these increments on film, and color coding each increment to produce

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a display of signal amplitude in color. By calibrating each voltage increment

with respect to the thermal reference plates in the scanner and assuming linear

variation of signal amplitude with scene object temperature, a calibration of

each step in terms of temperature was obtained.

The width of the slicing interval was set by careful examination of the

ground truth data at the time of the overflight. The width of the slicing level

was usually taken as one-tenth the total voltage spread between the coldest and

the warmest target of interest. The actual slicing increment depended largely

on the greatness of variation in the object scene temperatures, which varies

greatly with time of day. The slicing levels at which the hot and cold references

occurred were recorded for later calibration of steps in terms of temperature.

Examples of each of the above processing techniques are shown below.

RESULTS

1969 Michigan Multispectral Mission

All multispectral video data, including photography, were examined for each

flight. In general, all the raw data were good, although some data were better

because the aircraft traversed the preplanned flight line more precisely. The

existence of cloud shadows over a portion of the flight line was a problem

occasionally, but data from one good run were obtained at each altitude for

every flight period.

Evaluation of Aerial Photography. The purpose of obtaining simultaneous

aerial photography along with the optical-mechanical scanner imagery was two-

fold: (1) to provide interpreter orientation on the multispectral imagery for

each flight and at every altitude over the research area, and (2) to provide a

basis for judgment of the exact external physical features of the bark beetle

attacked trees at the time of the multispectral overflights. The second purpose

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was important in evaluating a previsual condition in attacked trees, or one where tree foliage was not yet discolored from the normal green appearance.

The Michigan photography was generally acceptable in terms of exposure and coverage. However, the 150 mm focal length KB-8 cameras did malfunction several times leaving a gap in the large-scale coverage. All four of the P-220 cameras functioned properly and provided photographic coverage for all flights. In comparison to the original film, the color duplicates which we received had a considerable loss of color rendition. It is fortunate that we obtained aerial color and color infrared photography with our own airplane and cameras at the time of the multispectral mission, or the second purpose of obtaining aerial photograph would have remained unfulfilled.

Evaluation of Multispectral Imagery.

Channel optimization -- The digital optimum channel selection technique was tested on three classification problems: the first, a generalized forest type classification; the second, classifying three conditions of tree vigor in ponderosa pine; and the third, identifying nonfaded bark beetle attacked ponderosa pine.

The ordering of the spectrometer channels in the first problem, for which all signatures were given equal weight, is shown in Table 3.

At each step, the channels for which the average pairwise probability of misclassification is computed include all those channels previously selected plus the most recent addition to the set. Thus, by examining the effect of adding additional channels, it is possible to select the level of accuracy beyond which the addition of more channels adds little to accuracy. For example, in the case in Table 1, little additional improvement in classifying targets occurs after the fourth (underlined) channel is added.

The second problem was classification of healthy, faded beetle attacked, and old-killed ponderosa pine. In this problem all categories were given equal

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Table 3. Spectrometer channels in the order selected for classification of forest types.

Channel Number	Spectral Band (μm)	APPM[1]
10	0.80 - 1.00	0.1676
8	0.66 - 0.72	0.1197
1	0.40 - 0.44	0.0930
6	0.58 - 0.62	0.0714
2	0.46 - 0.48	0.0613
9	0.72 - 0.80	0.0535
5	0.55 - 0.58	0.0471
3	0.50 - 0.52	0.0414
4	0.52 - 0.55	0.0360
7	0.62 - 0.66	0.0313

[1]Average pairwise probability of misclassification.

weight so that the channel choice would be equally influenced by the misclassification of one object as any other. The results agree with SPARC ordering calculated for the 1968 channel optimization (Table 4).

The 0.80 - 1.00 μm channel, which was first choice in the general classification, is last choice in the pine-type classification. The blue-violet channel was chosen as best, and among the first six choices two are in the red (channels 7 and 8), two in the green (channels 5 and 6), and two in the blue (channels 1 and 2).

The third and most difficult problem was the classification of healthy versus green, beetle attacked ponderosa pine. In this case only one pair of signatures existed. Compared with the classification of healthy, faded attacked and old-killed trees, the channel ordering was somewhat different (Table 5).

Among the best six channels for this problem were four of the best six channels for the second problem and only two of the best six channels for the general classification problem. Thus, the choice of optimum channels for SPARC analysis, for example, is influenced by the nature of the classification problem. The results clearly suggest that the digital channel optimization routine be used as the forerunner of a SPARC operation, especially when a priori knowledge is lacking for a classification problem.

Even when all ten channels of data were used for classification, in the third problem there was still an APPM of about 11 percent between healthy and green, attacked ponderosa pine. This is mediocre performance using all ten available registered channels and attests to the difficulty of the problem in using visible and photographic (near) infrared data exclusively.

Thermal digital.-- The thermal infrared (8 - 14 μm) analysis was displayed digitally as a computer-produced graymap with density of the computer printout calibrated to thermal radiance (Figure 10). In order to provide the

Table 4. Spectrometer channels in the order selected for problems in classifying vigor in ponderosa pines.

Channel Number	Spectral Band (μm)	APPM[1]
1	0.40 - 0.44	0.3260
6	0.58 - 0.62	0.2636
5	0.55 - 0.58	0.2084
2	0.46 - 0.48	0.1820
7	0.62 - 0.66	0.1532
8	0.66 - 0.72	0.1292
9	0.72 - 0.80	0.1110
3	0.50 - 0.52	0.0957
4	0.52 - 0.55	0.0790
10	0.80 - 1.00	0.0700

[1]Average pairwise probability of misclassification.

Table 5. Spectrometer channels in the order selected for problems in classifying nonfaded, green beetle attacked ponderosa pine.

Channel Number	Spectral Band (μm)	APPM[1]
8	0.66 - 0.72	0.4304
3	0.50 - 0.52	0.3823
4	0.52 - 0.55	0.3273
7	0.62 - 0.66	0.2621
5	0.55 - 0.58	0.2297
6	0.58 - 0.62	0.1811
1	0.40 - 0.44	0.1570
9	0.72 - 0.80	0.1358
2	0.46 - 0.48	0.1187
10	0.80 - 1.00	0.1087

[1]Average pairwise probability of misclassification.
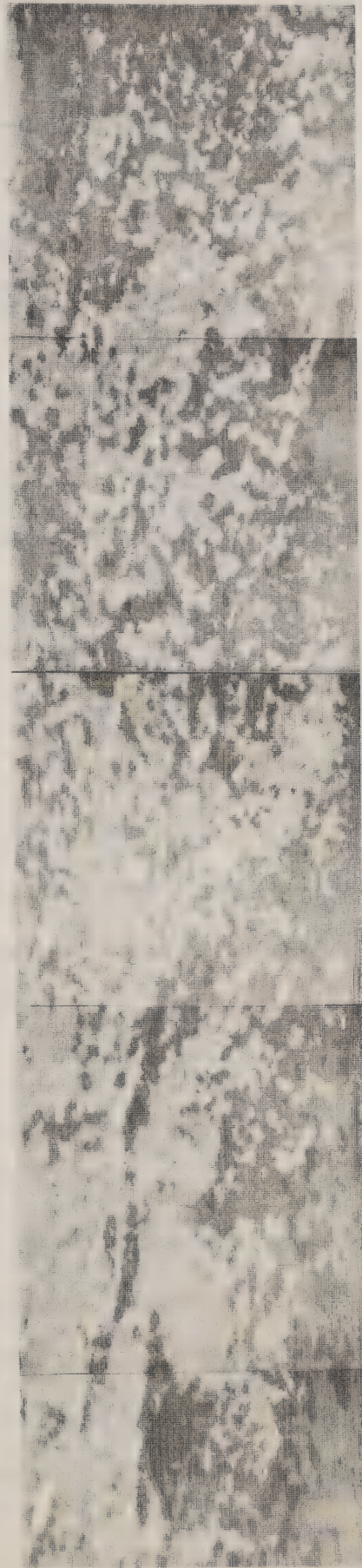
Figure 10. Strip image (top) is a direct printout of 8.2 – 13.5 μm video data collected over the Black Hills test site at 1325 hours on July 21, 1969. Thermal graymap (bottom) was produced by special single channel processing of the same thermal data shown above on Michigan's 1604 computer at the Willow Run Laboratories. In the photo above, areas of light tones are associated with high thermal radiance values and dark tones are the lower thermal radiance values. The reverse is true for the thermal graymap below.

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best thermal sensitivity, the grayscale was usually kept within the range of thermal radiance measured over the vegetation. The dynamic range of recorded thermal radiance was large for the entire 2-mile flight line. The greatest contrast was between trees and soil/rock outcrops, with the soil and rock having the higher values. When the graymap characterization was spread over the entire range of radiance values, sensitivity was lost for the forest.

Digital graymaps of the thermal infrared data provided an intermediate step in the analysis but were not the end point. It is obvious--for such a difficult problem as identifying stress in trees on the basis of higher radiant exitance--that more rigorous analytical methods are needed than one which uses only 25 percent of the available data. Although 15 to 20 point samples were digitized for each tree crown, only 4 or 5 of those sample points showed up on the graymap. This of course was sufficient for recognizing large targets having 4-5° C. thermal contrast with the surrounding background. One such target of interest which showed up on most of the graymaps, regardless of sensitivity, was a rather large group (25-30 trees) of old-killed beetle attacked trees. This thermal detection resulted from the opening of the forest canopy-- formerly occupied by healthy trees--which produced a higher thermal radiance than the surrounding healthy trees.

The status of thermal detection of green beetle-attacked trees using digital analyses will remain unresolved until we can analyze the digital tapes in detail with the yet to be written thermal discrimination program. There were locations on the thermal graymaps--especially the ones with expanded sensitivity--with indicated higher thermal radiance values which corresponded in location with known green beetle attacked trees. However, the graymap is still too coarse both in positional accuracy and thermal sensitivity to resolve the question.

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10-Channel SPARC -- Black Hills training sets for SPARC recognition
of 10-channel spectrometer (0.4 - 1.0 μm) data were: (1) healthy ponderosa pine,
(2) beetle-attacked pine (with yellow-green foliage discoloration), (3) dead
beetle-attacked pine (old killed) with few red needles, and (4) hardwood trees.

When spectral recognition parameters had been established within the
SPARC computer, Euclidean distance and likelihood ratio recognition maps were
made for each classification type. Recognition results were similar to those
from the 1968 Black Hills data (Weber, 1969). Hardwoods and dead beetle attacked
pine with little foliage retained were accurately identified by ground location
and group size. Because of the similarity with the 1968 recognition maps, no
effort was made to count recognition spots and once again develop the relation
of recognition spots to actual tree counts within each class. It was necessary
to use the highest threshold (1.95 volts) for accurate recognition of new-faded
beetle attacked pine. However, at that threshold some omission errors were
made, and, as in 1968, there was a fine line of threshold adjustment between
decreasing commission errors and increasing omission errors.

A new problem surfaced with the 1969 10-channel spectrometer data. Spectral
density ramping caused by changing terrain aspect and the attendent effect on
healthy pine irradiance caused problems for creating a representative spectral
model for that class. An accurate recognition model for healthy pine in general
was not adequate for the same class trees growing on steep southwest facing
slopes. Similarly, the adjustment to an accurate recognition model for healthy
pine on the southwest facing slope caused a significant degrading of recognition
of healthy pine elsewhere. In the future this problem can be dealt with by
improved computer programming for the preprocessing analysis and voltage signal
adjustment (Malila, 1968). Further, the addition of spectral information

between 2.0 and 3.5 μm to the recognition model for healthy fir would reduce the effect of signal ramping. This is because of little apparent ramping of the middle infrared data due to terrain aspect.

3-Channel SPARC -- Training sets for SPARC recognition of 3-channel infrared (1.0 - 1.4 μm, 2.0 - 2.6 μm, and 4.5 - 5.5 μm) data were (1) healthy ponderosa pine, (2) beetle-attacked pine (with yellow-green foliage discoloration), (3) dead beetle-attacked pine (old killed) with few red needles, (4) hardwood trees, (5) soil and rock outcrops, and (6) grassy clearings.

Careful attention was given to electronic gating procedures for rejecting extraneous point samples and spectral data from within each training set. This we found was important because of the small size and irregular shape of the training targets. The process of entering data into the SPARC computer and the adjustment of discrimination features was repeated several times until the best possible 3-channel recognition model was attained. After setup, both Euclidean distance and likelihood ratio recognition maps of each type were made (Figure 11). The likelihood ratio results were printed for each of several different voltage thresholds (1.25 - 1.95 volts) for each class of recognition.

Recognition of hardwoods, grassy clearings, and soil/rock outcrops was quite good, with thresholds between 1.50 and 1.75 volts being most satisfactory. The recognition of dead beetle-killed pines was similarly good except for some confusion related to the amount of red needles retained. Commission errors for this class were also made in areas near bare exposed soil. Healthy pines were recognized with only few problems, however, considerable errors were made in the classification of trees currently (at the time of the airborne mission) infested with bark beetles. The attacked trees with foliage which had already faded to yellow-red were identified, but there was much confusion in the classification of green and yellow-green beetle attacked trees. Most errors

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seemed to be related to topographic aspect. That is, trees on the level,

southfacing and westfacing slopes were accurately classified, but attacked

trees on northfacing and eastfacing slopes were mostly misclassified after 1100

hours. A reviewing of the three-channel video data revealed that much better

video contrast prevailed on data from early morning flights for identification

of beetle-attacked trees on the middle infrared data. This timing could be an

important consideration for the future.

Thermal contouring -- Thermal infrared data collected separately

in the 4.5 - 5.5 μm and the 8.2 - 13.5 μm wavelength bands were contoured

according to the hybrid processing technique described in the section "Procedures."

Analyses of the thermal data were performed on negatives which resulted from

the contour slices. Each contour step was labeled on the negative and the

apparent temperature calculated from calibration data. The contouring steps

were then compared to the original analog image and the target class represented

in any one step was identified using high-quality, large-scale aerial color

photography.

A complicating factor in the analysis of thermal responses from the forest

was that terrain objects were often detected on more than one contouring step

due largely to variations in radiant exitance[*] for the same class object occurring

on different terrain exposures. The uniqueness of a radiant exitance profile--

which could be differentiated from another object belonging to a different

class--was a function of season, time of day, and the long list of biophysical

and environmental factors we have discussed at length in past reports. Because

of the changing nature of thermal responses in forests it was necessary to

adjust the thermal calibration of the scanner to fit real time conditions in the

forest. We also performed contouring with intervals which realistically dis-

played forest classification types.

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*Radiant exitance is a newly defined term (1970) which describes the
radiant flux density measured at a surface. It replaces the former term "radiant
emittance" which has been deprecated.

D (1.0-1.4µm)

E (2.0-2.6µm)

F (4.5-5.5µm)

A

B

C

HEALTHY
CONIFER

DISEASED
CONIFER

OLD KILL
CONIFER

HARDWOOD

HDWD/CONIFER

SOIL/ROCK

G

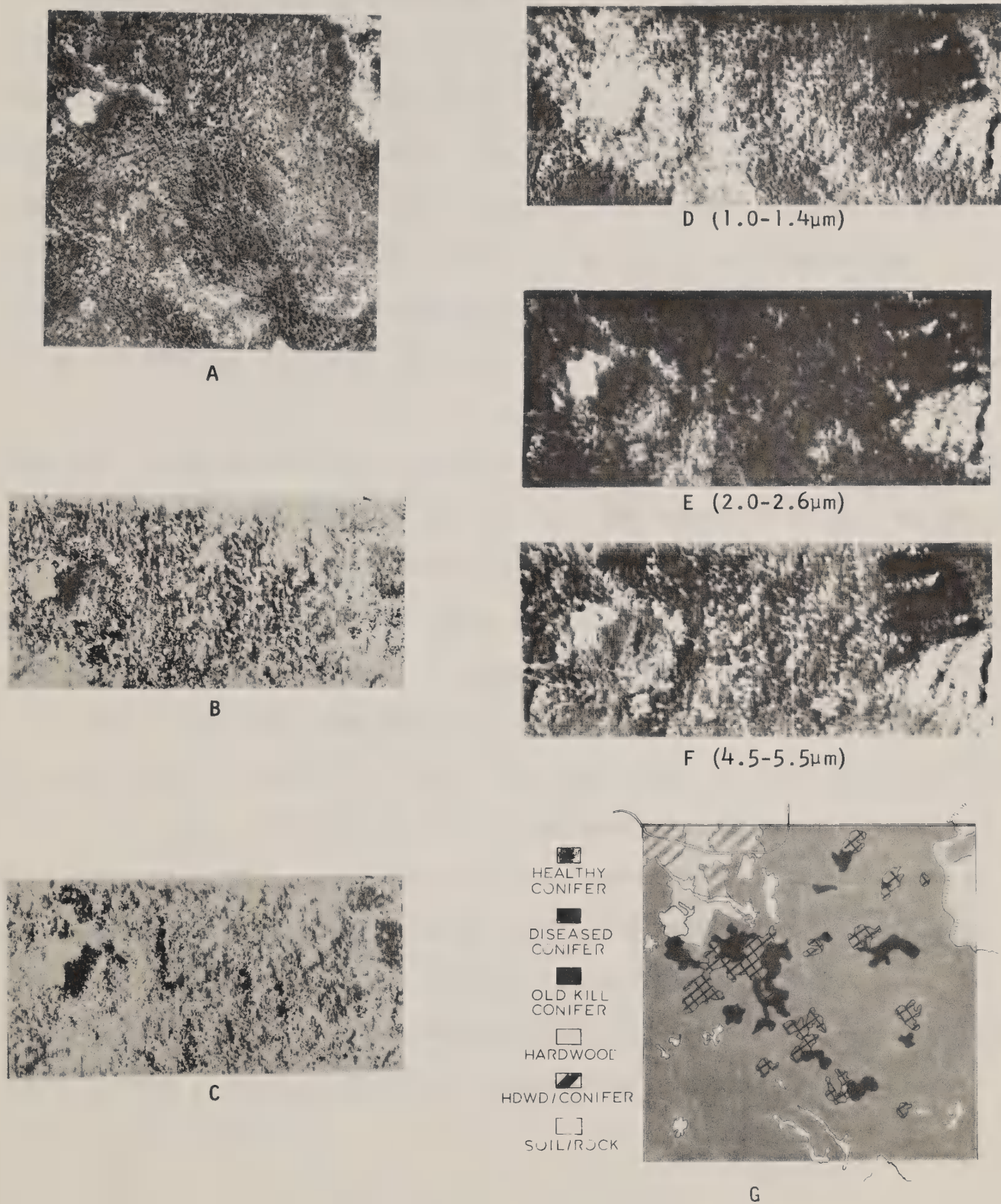Figure 11.   Color recognition maps--results of 3-channel SPARC processing--
             are shown for Euclidean distance and likelihood ratio analysis in
             (b) and (c). The results can be readily compared to the color
             aerial photograph (a) taken at the same time as the 3-channel video
             data (d through f). The type map (g) will aid in the interpretation
             of results.

Thermal separations were made on 8.0 - 14.0 m imagery at two different scales, one flown at 5,000 feet and one at 7,500 feet (above the ground), as shown in Tables 6 and 7. Table 8 shows the thermal separations made on 4.5 - 5.5 μm imagery flown at 5,000 feet. The color coded thermal signatures are displayed in Figure 12. We generally concentrated thermal analyses on data flown at the two higher altitudes. This was because we already had good information about separations that could be made on data collected close to the ground from the 1968 data. An important finding on 1969 data was that the microrecognition features (single tree profiles) are lost on 5,000 and 7,500 foot data. Data collected at 5,000 feet appear to be on middle ground between good microrecognition (at 1,500 feet) and good macrorecognition attained on the 7,500 foot data. At the highest altitude broad thermal features were apparent such as healthy pine type, large groups of beetle killed trees, hardwood patches, and the soils and rock outcroppings. The high altitude thermal data collected at 7,500 feet were also good for characterizing stand densities in the ponderosa pine forest. We felt it was significant to learn that 5,000 foot flying height, for collection of thermal infrared data, is not very good. If microrecognition features are required, then thermal scanning must be done at the lowest possible altitude above the forest. If on the other hand, a macro-recognition map based on thermal features in the forest will suffice, then a flying height of 7,500 feet (or perhaps higher) is reasonable. Horvath et al. (1970) provide a thorough discussion of the effects of altitude on airborne multispectral sensor data.

Table 6. Detailed key to thermal contouring steps for Black Hills data,
July 21, 1969 at 1400 hours. Data were collected at 5,000 feet
above the terrain with a thermal infrared detector operating
in the wavelength band of 4.5 - 5.5 μm. Color coded thermal
contour shown in Figure 12(C).

Step No.*	Temp. (^{O}K.)	Color Code	Target
10000	296.0	yellow	grass
10001	297.0	green	hardwoods
10011	297.5	blue	hardwoods with few conifers
10101	298.0	purple	conifers with few hardwoods
10111	298.5	red	conifers at normal density
11000	299.5	cyan	open grown and dead conifers
10010	301.0	sepia	beetle attacked conifers
10110	304.0	rust	exposed soil, grass, and trees
10100	306.0	amber	sparse conifers and grass over bare soil
01111	313.0	white	exposed rock and soil

*Binary representation of contouring levels.

Table 7. Detailed key to thermal contouring steps for Black Hills data, July 21, 1969 at 1330 hours. Data were collected at 7,500 feet above the terrain with a thermal infrared detector operating in the wavelength band of 8.2 - 13.5 μm. Color coded thermal contour shown in Figure 12 (E).

Step No.*	Temp. (^{O}K.)	Color Code	Target
01110	297.5	rust	hardwoods
10000	298.5	purple	conifers at normal density
10011	300.0	cyan	open grown and beetle attacked conifers
10101	302.5	amber	dead conifers, sparse trees, and grass over bare soil
11000	311.0	red	exposed rock and soil

* Binary representation of contouring levels.

Table 8. Detailed key to thermal contouring steps for Black Hills
data, July 21, 1969 at 1400 hours. Data were collected at 5,000
feet above the terrain with a thermal infrared detector operating
in the wavelength band of 8.2 - 13.5 μm. Color coded thermal con-
tour shown in Figure 12 (F).

Step No.*	Temp. (^{O}K.)	Color Code	Target
10001	297.0	yellow	hardwoods
10011	297.5	green	hardwoods with few conifers
10111	298.5	cyan	conifers at normal density
11000	299.5	lt. blue	open grown and dead conifers
10010	302.0	dk. blue	beetle attacked conifers and exposed soil with grass
11010	303.0	dk. brown	beetle attacked conifers and exposed soil
10110	304.0	amber	exposed soil, grass, and trees
10100	306.0	sepia	sparse conifers and grass over bare soil
01111	313.0	red	exposed rock and soil

* Binary representation of contouring levels.

HEALTHY
CONIFER

DISEASED
CONIFER

OLD KILL
CONIFER
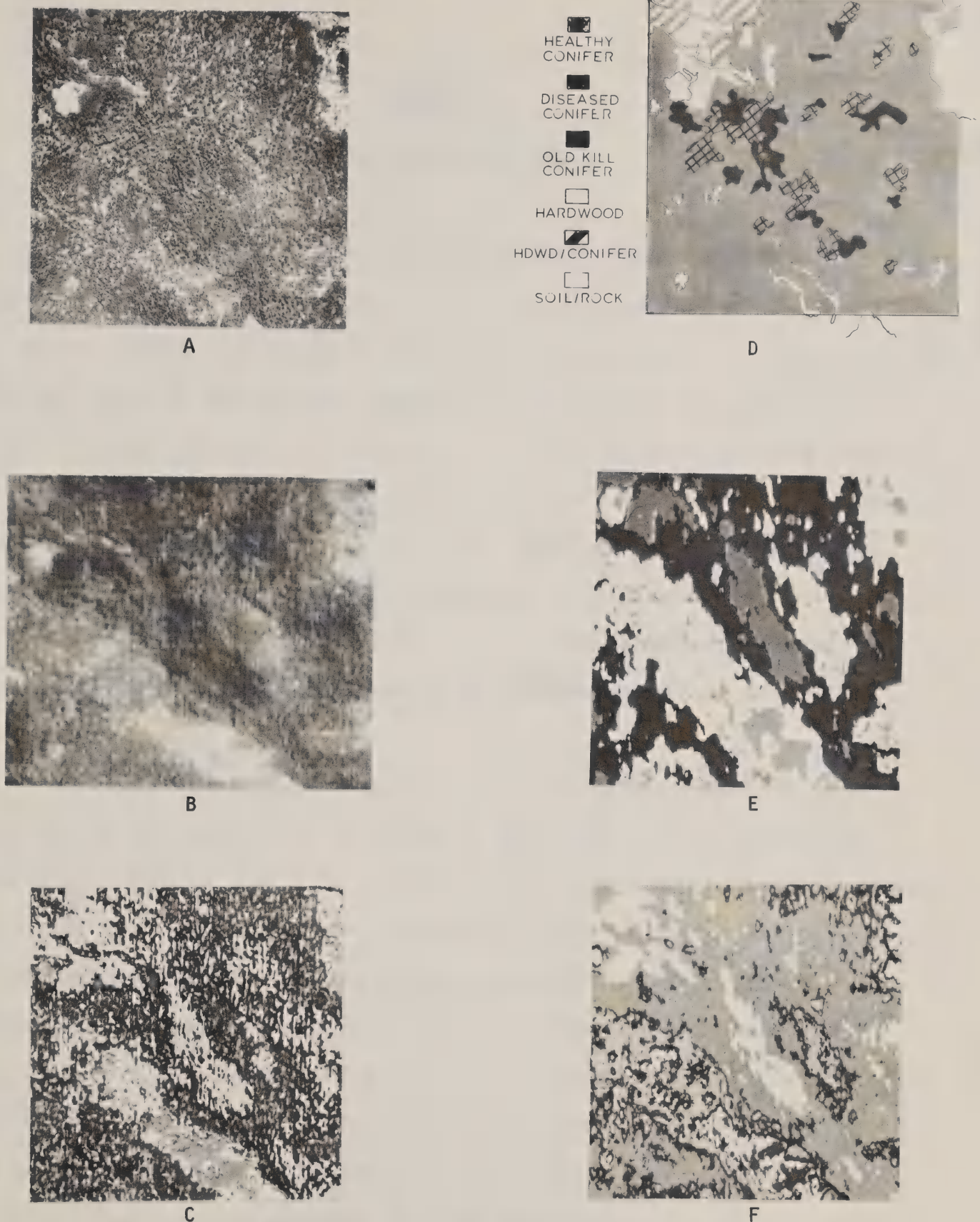
HARDWOOD

HDWD/CONIFER

SOIL/ROCK

Figure 12. Aerial color photo (A) and map type (D) aid in the interpretation
of color coded thermal recognition maps (Ec, E, and F). The 8.2 -
13.5 μm video analog data (B) is the same 5,000 foot altitude data
displayed in the color coded thermal contour (F). Color coded
thermal contourings are shown for 4.5 - 5.5 μm data flown at 5,000
feet (C) and 8.2 - 15.5 μm data flown at 7,500
feet (E).

SUMMARY

SMALL SCALE AERIAL PHOTOGRAPHY

Results of the August 1969, RB-57 high-flight experiment are inconclusive. Inadequate photographic coverage of the pre-selected sample strips prevented a reliable quantitative analysis along the study guidelines. An equally vexing problem, where we were provided adequate flight coverage, was that almost all films were underexposed. Unfortunately, the detection of bark beetle infested pine, even with low-altitude photography, requires films that have been properly exposed within a narrow exposure latitude. Exacting exposure is even more critical with photography that has been exposed at high altitude owing to the reflectance integration effect which increases with atmospheric pathlength and tends to reduce contrast between objects of dissimilar spectral reflectances.

Information that could be taken from this experiment seemed to agree with our earlier research on the effect of photographic scale on spot size detection. That is, generally, as photographic scale decreases and infestation spot size decreases, then photo interpretation accuracy decays accordingly. Due to the problems of obtaining adequate photographic coverage and good film exposure, the objectives of determining best film/filter combinations and evaluating the effectiveness of a large area survey remain unresolved. Because of the importance of all the objectives in this study, and the way they tie in with the interpretation of ERTS data, we are eager to rerun the experiment with improved operating standards of RB-57 photography.

MULTISPECTRAL SCANNING IMAGERY

The applications of airborne multispectral remote sensing and the potential of automatic multispectral processing for detection and classification

of stress in a ponderosa pine forest were investigated. Optical-mechanical line scanners and an array of aerial reconnaissance cameras were flown by the University of Michigan's Willow Run Laboratories over our research site in the Black Hills National Forest of South Dakota. The overflights of July 1969 resulted in our obtaining excellent quality multispectral imagery at 3 altitudes and 4 different times of day in 18 discrete channels between 0.4 and 13.5 μm.

Analog and digital methods of multispectral image processing that have been developed with Michigan's scientists the last six years were used to classify forest types and identify damage to ponderosa pine trees from attacks by the mountain pine bark beetle. Multiple channel processing of registered data was achieved in two spectral areas (0.4 - 1.0 μm and 1.0 - 5.5 μm), and specialized single channel processing was used for thermal infrared data in the 8.0 - 14.0 μm wavelength band.

This year we successfully implemented our theories of the past regarding the use of the best features of both analog and digital processing techniques in a further step toward achieving automated image processing and recognition. A specially adapted digital preprocessing program was applied to the 10-channel spectrometer data to remove unwanted variation in the raw data due to angle effects, shadows, and scanner nonuniform response over the total field of view. This phase was partially successful; however, we now know where additional programming effort in this vital area can improve results substantially. Michigan's digital program for spectral (spectrometer) channel optimization and ordering was modified to deal with our Black Hills forest parameters. Classification errors were computed for three recognition problems at each level as spectral channels were added to the total 10-channel ordering. The benefit of digital optimization was realized with time saved in setting up the analog (SPARC) processor.

A significant contribution this year was derived from our processing effort with 3-channel infrared data (1.0 - 1.4 μm, 2.0 - 2.6 μm, and 4.5 - 5.5 μm). In the past, classification errors were made in identifying tree vigor when only visible and near infrared spectral channels were used. It is apparent from our current research that it would be beneficial to extend the spectral range of the present spectrometer into the thermal infrared. We found that data in the wavelength band 2.0 - 2.6 μm, when added to the existing registered channels, reduced classification errors significantly. This was prticularly true with early morning data flown prior to 1000 hours.

Successful thermal separations were made on imagery in the 8.0 - 14.0 μm wavelength band for correctly classifying forest species, stand densities, and to a certain extent tree vigor. Although apparent radiance values were very similar for most tree vigor classes, identification of class boundaries was achieved by thermal contouring. We recognize the continuing problem of detecting the same object on more than one contouring step. This is due in part to the requirement of creating narrow contour classes, but also occurs when slope and target aspect (with respect to sun angle) change. We have cited the example of pine trees in the same condition class growing on dif-ferent slopes which were revealed in several different contour (or thermal) steps. In the future we expect to improve thermal recognition of tree vigor with more rigorous digital preprocessing.

In appraising the effect of flight altitude on recognition we discovered that increasing atmospheric pathlength by 3,500 or 6,000 feet caused some serious problems with degrading spectral recognition. Ordinarily, this relatively small increase in flying height has little effect on multispectral recognition. However, forest recognition problems at one or more stages in the data processing

program are highly dependent on ground resolution which is best at lower altitudes.

The potential for improved processing results will be achieved when multispectral scanners are available which provide for a common field stop for all channels, or at least a common instantaneous field of view, in the visible, near infrared and thermal infrared regions. It may be necessary to design and construct special systems owing to the requirement of high spatial resolution to achieve a high sampling rate for small crown diameter trees. This high spatial resolution must be attained without sacrificing signal-to-noise ratio capability which relates to the minimum detectable differences in temperature.

Hopefully, Michigan's newly redesigned scanner and the NASA/Bendix 24-channel scanner will meet our well-defined requirements for multispectral work in forestry. If either or both systems perform to expectation, the greatest and most direct benefit to forest biologists will be the previsual detection of stress in bark beetle infested trees. As we are now able to show some detection success working independently with each of three spectral band-widths ($0.4 - 1.0$ µm, $1.0 - 5.5$ µm and $8 - 14$ µm), the availability of simul-taneously registered data covering the entire bandwidth in narrowband incre-ments should yield large improvements in accuracy of stress situation.

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APPENDIX

The following is a list of U. S. Department of Agriculture, Forest Service personnel who have made contributions to this research study and represent a major salary contribution to it.

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